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National Aeronautics and Space Administration

BODY OF KNOWLEDGE FOR SILCON CARBIDE POWER ELECTRONICS

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Executive Summary

Wide bandgap (WBG) semiconductors, such as silicon carbide (SiC), have emerged as very promising materials for future electronic components due to the tremendous advantages they offer in terms of power capability, extreme temperature tolerance, and high frequency operation. This report documents some issues pertaining to SiC technology and its application in the area of power electronics, in particular those geared for space missions. It also serves as a body of knowledge (BOK) in reference to the development and status of this technology obtained via literature and industry surveys as well as providing a listing of the major manufacturers and their capabilities. Finally, issues relevant to the reliability of SiC-based electronic parts are addressed and limitations affecting the full utilization of this technology are identified.

Acronyms

AARM	Asteroid Robotic Retrieval Mission
AC	Alternating Current
ASIC	Application Specific Integrated Circuits
BOK	Body of Knowledge
CAD	Computer-Aided Design
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
DLR	German Aerospace Center
ESA	European Space Agency
FCS	Future Combat Systems
FIT	Failure-In-Time
GaN	Gallium Nitride
IGBT	Insulated-Gate Bipolar Transistor
JAXA	Japanese Aerospace Exploration Agency
JBS	Junction Barrier Schottky
MOS	Metal-Oxide-Semiconductor
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
NASA	National Aeronautics and Space Agency
NEPP	NASA Electronic Parts and Packaging
NREL	National Renewable Energy Laboratory
PCU	Power Control Unit
PFC	Power Factor Correction
PPU	Power Processing Unit
$R_{DS(ON)}$	On-State Drain-Source Resistance
SEB	Single-Event Burnout
SEE	Single-Event Effect
SEGR	Single-Event Gate Rupture
SEP	Solar Electric Propulsion
Si	Silicon
SiC	Silicon Carbide
SOI	Silicon-On-Insulator
SSIM	Smart Sensors and Integrated Microsystems
TA	Technology Area
TID	Total Ionization Dose
UAV	Unmanned Aerial Vehicle
UPS	Uninterruptible Power Supply
WBG	Wide Bandgap

Background

Integrated circuits and power devices utilized by the semiconductor industry for the production of advanced computers, consumer electronics, communication networks, and industrial and military systems have been almost exclusively based on silicon (Si) technology. The requirements of future electronics place a great emphasis on achieving new devices with greater power density and energy efficiency, especially in the power electronics arena. This emphasis poses an increasing challenge to come up with new design protocols, innovative packaging, and even new semiconductor material as it is widely believed that silicon technology has finally reached its fundamental physical limits. In addition to the devices' electrical requirements such as voltage and power rating, the operational environment of the power system might encompass challenging conditions that include radiation, extreme temperature exposure, wide-range thermal cycling, etc., where conventional silicon-based systems are incapable of survival or efficient operation.

Wide Bandgap Technology

WBG semiconductor devices, such as those based on SiC or gallium nitride (GaN), have emerged in the commercial market and are expected to gradually replace traditional silicon parts in the high power area. SiC and GaN semiconductor materials offer three main benefits over their silicon counterpart in power applications: greater efficiency at higher voltage, higher temperature operation, and higher frequency switching [1]. Compared to 1.1 eV for Si, the bandgaps of SiC and GaN are 3.3 eV and 3.4 eV, respectively. A wider bandgap results in a higher critical electric field, which, together with a lower dielectric constant, translates to a lower on-state resistance for a given blocking voltage. The wider bandgap also enables higher-temperature operation before the device "goes intrinsic," that is, before the intrinsic carrier density exceeds the donor impurity density. SiC and GaN are stiffer materials than Si, resulting in higher optical phonon energies and thus higher saturation velocities as compared with Si. The higher saturation velocities of these WBG materials offset the relatively lower electron mobility to enable faster switching speeds and higher current density as compared to Si [1]. Finally, SiC offers a higher thermal conductivity than that of both GaN and Si due in large part to the higher longitudinal acoustic velocity of SiC, allowing efficient heat transfer (note that although both SiC and GaN are stiffer than Si, GaN's acoustic velocities suffer from the higher material density). Some material properties of SiC and GaN as compared with Si are listed in Table I [2]-[3].

Table I. Relative comparison of semiconductors [2]-[3].

Property (relative to Si)	**Si**	**SiC**	**GaN**
Thermal Conductivity	1	3.1	0.9
Thermal Expansion Coefficient	1	1.6	2.2
Dielectric Constant	1	0.9	0.9
Electron Mobility	1	0.67	0.83
Hole Mobility	1	0.08	0.42
Breakdown Electric Field	1	7.34	6.67
Saturation Velocity	1	2	2.2
Maximum Working temperature	1	5.2	5.34

The benefits of WBG materials described above allow the development of a new generation of devices that are smaller, faster, and more efficient, with ability to withstand higher voltages and higher temperatures. The combined higher switching speed and efficiency of transistors, for example, allows the operation of DC/DC converters at very high frequencies, thereby reducing weight, saving board space, and conserving power [3]. Although WBG power devices show great promise and are considered to be potential candidates for use in emerging applications, there exist some limitations that hinder full potential utilization. For instance, the majority of GaN devices are grown on a Si substrate due to cost consideration, thereby introducing a lattice mismatch and resulting in fabrication defects [4]. However, improvements have been reported recently on the GaN-on-Si epitaxy techniques [5]. While SiC has the potential to operate up to at least 600 °C [2], or even 760 °C [1], it also suffers from manufacturing defects that reduce yield, and sometimes can be cost prohibitive. The initial overall cost of SiC, however, may be offset by satisfying the need for operable and reliable systems geared for unique applications.

Silicon Carbide Devices

The advantages of SiC over Si for power devices include lower losses leading to higher overall system efficiency, and higher breakdown voltages. SiC can operate at higher temperatures, thereby permitting higher switching speeds. It also has excellent reverse-recovery characteristics which lead to reduced switching losses and to lower electromagnetic interference, thereby eliminating or reducing the need for snubbers [2]. Because of the low switching losses, SiC devices can operate at higher frequencies resulting in smaller capacitive and inductive components which, in turn, reduce size, weight, and cost of power systems. In addition, the thermal conductivity of SiC is three times that of Si, as noted in Table I, and the majority of this WBG material's properties are not significantly influenced by temperature variation [6]. The $R_{DS(ON)}$ of a 1200 V SiC MOSFET, for example, increases only 20% over operating temperature compared with over 250% for a 1200 V silicon MOSFET [7], and in device modeling, the inversion layer mobility in SiC may be considered constant over the temperature range of 27 °C to 325 °C [8]. High temperature operation coupled with low loss results in high efficiency SiC devices with reduced cooling/thermal management requirements. Such benefits reduce overall system cost and result in smaller form factors [6]. SiC Schottky diodes and transistors are the most developed WBG components in part due to their excellent performance and applicability in design of power circuits. According to [9], the French research firm Yole Developpement estimates that when SiC replaces Si in power circuitry the efficiency of DC/DC conversion could increase from 85% to 95%, AC/DC conversion from 85% to 90%, and DC/AC conversion from 96% to 99%. These attributes, among others, render SiC devices ideal for high power (>1200 V, >100 kW), high temperature (200 °C to 400 °C) applications and, despite their cost, these devices are increasingly being adopted in many markets [6]. Even at low voltages around 200 V, SiC devices demonstrated superiority in terms of efficiency as their switching losses exhibit a very slight increase with temperature as compared to their Si counterparts [10]. In 2014, the SiC chip business was estimated to be worth more than US $133 million with SiC diodes representing more than 80% of the global market, and the growth in both diodes and transistors is expected to more than triple by 2020, reaching over US $436 million [11]. Other forecasts suggest that the market penetration of SiC devices, particularly power-level, will continue to grow reaching around $2 billion in the next ten years [12], spanning various fields including space, military, industrial, and commercial applications [13].

NASA Technology Roadmap

"By 2025 we expect new spacecraft designed for long journeys to allow us to begin the first ever crew missions beyond the Moon into deep space," President Obama said. "So, we'll start by sending astronauts to an asteroid for the first time in history. By the mid-2030s, I believe we can send humans to orbit Mars and return them safely to earth, and a landing on Mars will follow" [14].

Development of new technologies, spanning from structural material and propulsion to electronics and health monitoring, will be required to achieve deep space missions. Therefore, innovative research and design need to overcome the numerous technical challenges anticipated to render these endeavors successful. The emerging SiC technology is considered to be a prime candidate for addressing and meeting requirements pertaining to electronics and power management. Power devices based on SiC offer many benefits and are in some ways well suited for application in the harsh environment of space where traditional electronics fail to survive, or require special control or enclosures resulting in weight and cost penalty and affecting reliability. Some of the space and aeronautics missions where SiC power electronics could potentially be applied are shown in the NASA Technology Roadmap listed in Table II [14].

Table II. Partial listing of NASA Technology Roadmap [14].

Technology Area	Capability Needed	Challenges	Mission	Launch Date
TA 4: Robotics and Autonomous Systems	4.3.1.3: Integrated control and power electronics for motor controllers and actuators	Small form factor, more efficient power, and extreme space environment	New Frontier: Lunar Sample Return Planetary Flagship: Mars Sample Return Exploration: Crewed to Lunar Surface Exploration: Crewed to Mars Moons	2024 2026 2027 2027
TA 3: Space Power and Energy Storage	3.3.5: Advanced power processing units and high voltage, high temperature, rad hard power switches, diodes, and passive devices	Reliable, high voltage, low loss, rad hard devices for high-power electric propulsion system and space environment	Into Solar System: Asteroid Redirect Planetary Flagship: Europa Exploration: Crewed to Lunar Surface Exploration: Crewed to Mars Moons New Frontier: Io Observer	2022 2022 2027 2027 2029
TA 10: Nanotechnology	10.4.2.3: Fault-tolerant, extreme-environment Schottky diodes, switches for computing, logic gates, and memories	High speed, robust Schottky diodes and electronics for long-term operation in harsh environment	New Frontier: New Frontier Program 4 Planetary Exploration: Crewed Mars Orbital	2024 --
TA 15: Aeronautics	15.4.2.1: Alternative propulsion system (hybrid/electric)	High power, high density motors, and wide temperature range electronics and controllers	Ultra-efficient, environment-friendly vehicles	--

In addition to supporting NASA missions, as stated earlier, SiC technology may be beneficial in supporting exploration and science missions being pursued by other government agencies, commercial sectors, and communication and aerospace industry. The following is a listing of some specific markets where SiC power devices might be good candidates for utilization [12, 13]:

- ***Commercial***
  - Power factor correction (PFC)
  - Motor drives
  - Uninterruptible power supplies (UPS)
  - Photovoltaic inverters
  - Power utilities, energy conversion, power distribution
  - Automotive industry (hybrid/electric vehicle)
  - Industrial equipment
  - Consumer electronics, data and communication networks
  - Down-hole drilling

- ***Military***
  - Communication and strategic satellites
  - High-energy laser and advanced armament
  - All-electric planes and boats
  - Unmanned aerial vehicles (UAV)
  - Next generation warships
  - Armored robotic vehicles

- ***Aerospace***
  - High altitude aircraft
  - Sensors and imaging systems onboard satellites
  - Data communication and networking

SiC Technology Status

SiC semiconductors are available today from various manufacturers as well as small start-up business firms. While some supply discrete parts such as Schottky barrier diodes, transistors, and thyristors, others offer customized application specific integrated circuits (ASICs) that include digital, analog, and mixed circuits. A handful of these companies provide some of these devices in bare die form for high voltage (1200 V) diodes and metal-oxide-semiconductor field effect transistor (MOSFETs) or in the form of integrated modular power packages that include silicon insulated-gate bipolar transistors (IGBTs) and SiC rectifiers. A listing of some of the major manufacturers/providers of SiC electronic parts is shown in Table III. It is important to point out that although this information was obtained via thorough industry and literature search, it does not, however, include all organizations involved in the production of SiC electronic components due to issues relating to proprietary information, lack of public reporting, still-under-development status, etc.

Table III. Major providers of SiC electronic parts.

Manufacturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
Wolfspeed (Cree)	Schottky diode MOSFET Modules Bare die Automotive qualified Schottky diode Evaluation boards Spice model	600-1700V, 1-50A, TO & QFN package 900-1700V, 2.6-71A, TO & D2PAK package 1200-1700V, 20-300A 900-1700V, 1-71A 600-650V, 1-20A, TO & QFN package	Available	Data sheets, application notes, design files, reliability report "SiC Zero recovery at High Voltage Slew rate" http://www.wolfspeed.com/power/document-library	http://www.wolfspeed.com/
Infineon	Schottky diode JFET Modules Evaluation boards Spice model	600-1200V, 2-40A, TO & DPAK package 1200V, 26-35A, TO-247 package 650-1200V, 30-600A	Available	Data sheets, application notes, design files, reliability report (request)	https://www.infineon.com/
Fairchild Semiconductor	Schottky diode Spice model	1200V, 15-40A, TO package	40A available, 15-20A in production	Data sheets, application notes, reference design, reliability report (request)	https://www.fairchildsemi.com/search/?searchText=SiC+diode

Table III. Major providers of SiC electronic parts (Cont'd).

Manufacturer	**Part/ Product**	**Capability/ Specification**	**Product Status**	**Relevant Information**	**Reference**
GeneSiC	Schottky diode Junction transistor (SJT) Modules Bare die Evaluation boards Spice model	650-1200V, 2.5-100A, TO & SMB/DO package 1200-1700V, 15-160A, TO, SOT, & DPAK package 1200V, 25-160A, TO & SOT package 600-1200V, 1-100A	Available as: Commercial line (175 °C) High temperature line (210 °C)	Data sheets, application notes, technical articles, reliability reports "1200 V SiC Junction Transistor (SJT) Devices" and "1200 V SiC Schottky Rectifiers" http://www.genesicsemi.com/quality/reliability/	http://www.genesicsemi.com/
ROHM	Schottky diode MOSFET Modules Bare die Automotive qualified Schottky diode Spice model	650-1200V, 5-40A, TO package 400-1700V, 3.7-40A, TO package 1200V, 120-300A 650-1200V, 10-55A 600-650V, 1-20A, TO & QFN package	Available (Inquiry for bare die)	Data sheets, application notes, reference design, reliability report (request) http://www.rohm.com/web/global/design-support/quality-a-reliability http://rohmfs.rohm.com/en/products/databook/applinote/discrete/sic/common/sic_appli-e.pdf	http://www.rohm.com/web/global/
Allegromicro/ Sanken	Schottky diode	650V, 5-20A, TO package	In production	Data sheets, design support, test and reliability reports (request)	http://www.semicon.sanken-ele.co.jp/ctrl/en/product/list/SiC_SBD/

Table III. Major providers of SiC electronic parts (Cont'd).

Manufacturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
STMicroelectronics	Schottky diode MOSFET Automotive qualified Schottky diode Evaluation boards Spice model	600-1200V, 4-12A, TO & DPAK package 1200V, 20-45A, HiP247 package 650V, 12A, TO & DPAK package	Available	Data sheets, application notes, reference design, reliability report (request)	http://www2.st.com/content/st_com/en.html
SemeLab/ TT Electronics	Schottky diode MOSFET Modules ProEngineer model	600-1200V, 1-20A, TO, LCC3, DLCC2, & SMD package 650V, 25A, SMD package On demand	Some parts are stock available (off-the-shelf)	Data sheets, application guidelines, reliability report "Cree SiC High Temperature Reliability Trials" using Cree die: http://products.semelab-tt.com/pdf/diode/siliconcarbide/SiCDiodesReliabilityStudy.pdf ; http://www.semelab-tt.com/uploads/q-and-r-in-hi-rel.pdf	http://www.semelab-tt.com/uploads/SpaceBrochure.pdf
Toshiba	Schottky diode MOSFET Spice model	650-1200V, 6-24A, TO package 1200V	Available/ some require lead time In development	Data sheets, application notes, reliability report (request) http://toshiba.semicon-storage.com/eu/design-support/reliability/device/concept.html https://www.toshiba.co.jp/rdc/rd/fields/10_e07_e.htm	http://toshiba.semicon-storage.com/eu/product/diode/sic.html

Table III. Major providers of SiC electronic parts (Cont'd).

Manufacturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
United Silicon Carbide	Schottky diode JFET Bare die Spice model	650-1200V, 4-30A, TO package 1200V, 21-38A, TO package 650-1200V, 4-100A	Available Bare die (50-200A) as engineering sample	Data sheets, application notes, reference design, reliability report "1200 V xJ SiC Series 45 mΩ,1200V - Normally-on JFET Transistors Product Qualification Report" http://unitedsic.com/wp-content/uploads/2016/01/1200V_XJ_SIC_SERIES_RELIABILITY_DOCUMENTATION.pdf reliability report "1200 V xR SiC Series 1200 V-15A, 10A, 5A / 30A, 20A Schottky Diodes Product Qualification Report" http://unitedsic.com/wp-content/uploads/2016/01/PRODUCT_QUALIFICATION_REPORT_1200V_XR_SIC_SERIES.pdf reliability report "650 V xR SiC Series 650 V-10A, 8A, 6A, 4A / 20A, 16A Schottky Diodes Product Qualification Report" http://unitedsic.com/wp-content/uploads/2016/01/PRODUCT_QUALIFICATION_REPORT_XR_JBS_REV1.0.pdf	http://unitedsic.com/
	Schottky diode & JFET	1700V, 3300V, 4500V & 6500V	Demonstrated /under development Contact for part availability,	http://unitedsic.com/news/ http://unitedsic.com/wp-content/uploads/2016/02/SiC-Research-and-Development-at-United-Silicon-Carbide-Inc.-Looking-Beyond-650-1200V-Diodes-and-Transistors-March-2015.pdf	
	Normally-off JFET	6500V, 15A	Demonstrated/under qualification	http://ieeexplore.ieee.org/xpls/icp.jsp?arnumber=6964642	
Central Semiconductor	Schottky diode Bare die Spice model	650-1200V, 10A, TO & DPAK package 1200V, 10A	Available	Data sheets, application notes, reliability report (request) https://www.centralsemi.com/content/quality/reliability_data.php	https://www.centralsemi.com/
Raytheon	Wafer foundry	--	Internal/ request	Technology briefs, test results http://www.raytheon.co.uk/rtnwcm/groups/rsl/documents/content/rsl_semi_high_temp_article.pdf "Digital and Analogue Integrated Circuits in Silicon Carbide for High Temperature Operation"	http://www.raytheon.co.uk/capabilities/products/siliconcarbide/

Table III. Major providers of SiC electronic parts (Cont'd).

Manufacturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
Mitsubishi Electric	Schottky diode MOSFET Module Power loss simulator	600-1700V 600-1700V 1200V, 100-600A; 1500-3300V, 1500A	Available, prototype, and in-development parts	Data sheet, technical report "Low On-Resistance SiC-MOSFET with a 3.3-kV Blocking Voltage" http://www.mitsubishielectric.com/company/rd/advance/pdf/vol149/149_TR6.pdf http://www.mitsubishielectric.com/news/2014/pdf/0515.pdf http://www.mitsubishielectric.com/company/rd/advance/pdf/vol143/143_TR2.pdf	http://www.mitsubishielectric.com/search/search.html?q=SiC&image.x=7&image.y=9
Cissoid	Schottky diode MOSFET Module	1200V, 30A, HM8A package 1200V, 10A, TO package 1200V, 20-30A	Available	Data sheets, application notes, reliability report (request) http://www.cissoid.com/quality-and-reliability/	http://www.cissoid.com/
Microsemi	Schottky diode MOSFET Modules Spice model	650-1700V, 5-30A, TO, D3PAK, & SMD package 700-1200V, 26-70A, TO, D3PAK, & SOT package 600-1700V, 20-293A, SOT,D3PAK, & SP package	Available/ in production (Inquiry for bare die)	Data sheets, application notes, reference design, reliability report (request) http://www.microsemi.com/company/quality/reliability	http://www.microsemi.com/product-directory/discretes/3613-silicon-carbide-sic

Table III. Major providers of SiC electronic parts (Cont'd).

Manufacturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
Sensitron Semiconductor	Schottky diode MOSFET Modeling tools	300-1200V, 2-50A, TO, LCC, & SMD package 1200V, 20-31A, TO & LCC package	Inquiry/lead time	Data sheets, test and reliability reports (request)	https://sensitron.com/Hi_brochure/SiCSelector.pdf
Monolithic Semiconductor	MOSFET Wafer	>1700V 15cm	Prototype/in production	Prototype test result http://www.monolithsemi.com/Technology-Prototype.html	http://www.monolithsemi.com/ http://www.monolithsemi.com/2014_06_03-Monolith-press-release.pdf
General Electric	MOSFET Module	1200V, 26.5-34A, TO package; 1200 2200V 1700V	Unknown (Internal/collaborative)	Reliability http://www.rpi.edu/cfes/AnnualConference/B1%20Stevanovic%20Final.pdf APEC 2015 "Overview of 1.2kV – 2.2kV SiC MOSFETs targeted for industrial power conversion applications" http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7104691	https://www.ieeeusa.org/calendar/conferences/annualmeeting/2012/program/files/Friday/Track3/SiC-Power-Conversion-Smolenski.pdf
Panasonic/ Sancha Electric	Module	1200V, 150A	Contact distributor	Publication "Novel SiC Power MOSFET with Integrated Unipolar Internal Inverse MOS-Channel Diode" http://www.businesswire.com/news/home/20150303006907/en/Panasonic-Sansha-Electric-Jointly-Develop-Compact-SiC http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6131620 http://news.panasonic.com/global/press/data/2015/03/en150304-2/en150304-2.html	http://www.semicon.panasonic.co.jp/en/news/contents/2015/pcim/
Ozark IC	Customized circuits Modeling tools	Customized	Customized	Provide customized ASIC including digital, analog, and mixed circuits based on SiC	http://www.ozarkic.com/

Table III. Major providers of SiC electronic parts (Cont'd).

Manufacturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
Global Power Technologies Group	Schottky diode MOSFET Modules Bare die Spice model	600-1200V, 3-60A, various TO packages 600-1200V, 16-80A, TO-247 package 600-1200V, 10-80A, SOT-227 package 600-1700V, 3-50A	Contact distributor	Data sheets available, test and reliability reports (request)	http://www.gptechgroup.com/index.php/en/
Renesas Electronics	Schottky diode Spice model	600V, 10-30A, TO-220 & TO-3P packages	Contact distributor	Data sheets available, test and reliability reports (request)	https://www.renesas.com/en-us/products/diodes/sic-schottky-barrier-diode.html

The research, development, and application of SiC technology and devices are not only pursued by commercial entities, but include a broad spectrum of organizations. These range from non-profit institutions (academia), clean-environment advocate groups, civilian space agencies, and national defense departments. For instance, a public-private manufacturing innovation institute was established under an initiative by the White House [15] aimed at enabling the next generation of energy-efficient, cost-competitive, high power WBG-based devices, and for strengthening US manufacturing. This initiative led to the establishment of the US Department of Energy's PowerAmerica Institute, a consortium of 18 companies, 6 universities, and US federal government laboratories engaged in various WBG semiconductor activities. The majority of these tasks are focused on SiC technology [16] and pertain in part to issues relating to:

- Development of high voltage (1200 V to 10,000 V) SiC devices.
- Integration of a SiC MOSFET and Junction Barrier Schottky (JBS) diode to reduce chip area, improve efficiency and increase switching frequency.
- Investigation of novel edge termination and packaging for high voltage SiC devices.
- Qualification of 150 mm Si foundry for SiC processing, as well as the development of SiC foundry for commercialization and reducing manufacturing cost.
- Establishment of device manufacturing and qualification processes.
- Development of SiC modules with high efficiency, reduced size, and increased power density.
- Development of high power converters and inverters.
- Research and development of gate drive circuits for SiC devices to enable fast switching.
- Development of reliability tests, identification of failure mechanisms, and establishment of reliability standards.
- Establishment of electrical models for SiC JFETs and development of Spice circuit models and CAD tools.

NASA is actively involved in SiC material research for advanced semiconductor electronic applications [17], as well as the development of high voltage, power-level devices geared for aerospace and space environments. Applications include jet distributed engine control, hybrid aircraft, power processing units (PPUs) for high power solar electric propulsion (SEP), motor drives and actuators for Asteroid Robotic Retrieval Mission (ARRM), and probes and landers for high temperature environment space exploration (Venus 450 °C) missions. In addition to in-house projects, NASA is continually awarding small business innovation research (SBIR) funding and other research grants to industry and academia to enhance technology development for space applications. Developing SiC-based photonic sensors, extending the capability of SiC JFET circuit technology for extreme temperature and radiation operation, and improving performance of SiC MOSFETs under heavy-ion exposure, are some of these efforts pertaining to SiC technology [18]. The NASA Electronic Parts and Packaging (NEPP) Program, for example, addresses issues pertaining to reliability, in particular radiation effects, of WBG power devices. The NEPP Program also provides guidance for the selection and application of technologies for space use through performance evaluation, qualification guidelines development, risk determination, and reliability assessment [19]. One of the program-supported tasks addresses the effect of radiation, including heavy-ion exposure, on SiC-based electronics.

Other US Government Agencies supporting the development of SiC power devices include the Air Force Research Laboratory, the Naval Research Laboratory, and the Army Research Laboratory. For example, the Air Force Research Laboratory has established, funded, and led numerous collaborative programs on SiC MOS research and development work for over a decade [20]-[21]. Similarly, the Naval Lab extensively supported research and development activities ranging from growth of SiC semiconductors to fabrication and qualification of high voltage parts [22]. The US Army has funded internal and external SiC research ranging from material growth and MOS device physics to component design and packaging, through the Army Research Laboratory Sensors and Electron Devices Directorate and the (now-defunct) Future Combat Systems (FCS) hybrid-electric combat vehicle program [23]-[24].

Other activities related to SiC electronics technology include but are not limited to:

- Scientists at Wayne State University's Smart Sensors and Integrated Microsystems (SSIM) laboratory are developing a wide range of high-temperature and high-voltage devices using SiC technology [25].
- At the British University of Warwick, SiC and power electronics are a major research target of study at the school's special laboratory for materials physics and fabrication technology on SiC devices [25].
- The Electronics Manufacturing and Reliability Laboratory at Georgia Institute of Technology focuses on the fabrication, packaging, and reliability of SiC in collaboration with other universities and military and commercial organizations [26].
- Japanese Aerospace Exploration Agency (JAXA), is pursuing development of SiC semiconductors, notably diodes and power transistors, for space applications [27].
- SiC Power Center, a Swedish platform involving industry, research institutes and academia, was established in 2012 to promote introduction of SiC power electronics in high energy efficiency and high-temperature applications [28].
- German Aerospace Center (DLR) initiated a program in 2011 for the development, evaluation, and qualification of high voltage SiC diodes for space applications [29].
- European Space Agency (ESA), is sponsoring studies on development and reliability assessment of SiC power parts for potential future application in space missions [30].
- Efforts pursued by the automotive industry include Toyota's announcement of road test of SiC modules in Hybrid Camry [11], and Japan's Denso Silicon utilization of SiC devices in power control units (PCUs) for the Lexus hybrid electric vehicles [25].

Technology Limitations

Although SiC devices offer tremendous benefits when compared to their silicon counterparts, research and development efforts are continuing to mature this technology in order to fully exploit its advantages. Some of the challenges that are hampering the progress of this technology include:

Defects/Yield:

For SiC to replace Si as the prime semiconductor in the power electronics arena, improvement in the material's growth needs to be attained and optimized in order to produce high-quality, low-defect SiC wafers. Some of these defects include crystal and surface defects, dopant incorporation, and dislocations that are inherent to the substrate as well as the associated epitaxial layers. In comparison to silicon crystals, which have defect densities of less than 1 dislocation/cm^2, the defect density in SiC wafers are many orders higher in magnitude, approaching 1000 dislocations/cm^2 as of 2012 [25]. However, significant efforts have recently been made to address the quality of the SiC wafers including, for example, the introduction by Dow Corning Europe of a 150 mm SiC substrate with defect density of about 840 dislocations/cm^2 [31] and the offering by Showa Denko Europe of very low defect density SiC epitaxial wafers for power devices under the trade name of "High-Grade Epi - HE" [32]. In addition, Cree Inc., a global manufacturer of SiC substrates, is continually introducing very low micro-pipe defect, highly uniform epitaxial layers [33]. These developments along with recent advances in wafer fabrication, such as the NASA Glenn Research Center patented work on SiC large tapered crystal growth [34], would definitely lead to more efficient and cost effective SiC-based electronics.

Cost:

SiC presently maintains much higher wafer costs as compared to silicon. Improvement in yield density and availability of larger wafers, however, will speed up infiltration of this technology into bigger markets, resulting in overall cost reduction. With the recent progress in SiC epitaxial materials, large-size wafers are more readily available as evidenced by Cree's offerings of 76.2 mm to 150 mm wafers [35], Nippon Steel Corporation's successful development of 150 mm SiC single-crystal wafers [25], and, as stated earlier, Dow Corning's 100 and 150 mm wafers [36]. Some of the other commercial entities involved in this work include X-Fab, a silicon foundry that has upgraded its manufacturing resources to accommodate 150 mm wafers [37]-[38], and New York Power Electronics Manufacturing Consortium (NY-PEMC) which is a public-private partnership producing high performance power electronic devices using a 150 mm SiC fab [39]-[40]. Although 150 mm-size wafers are becoming mainstream now for SiC, efforts are underway to achieve larger wafers, with 200 mm-diameter wafers on the near horizon [41].

Device Packaging:

Due to the capability of SiC devices to operate at high temperatures and switch at high speeds, special measures are needed for the production of reliable and efficient SiC components. For example, special packaging, interconnects, attachments, etc. are needed to fully utilize their extreme temperature performance; the high switching speeds may necessitate the use of unique substrate attachment and printed circuit board layout to reduce inductive and capacitive parasitics. In addition, the high electric fields present during normal operation of SiC power devices require efforts to alleviate surface field enhancement due to structure irregularities, voids in the passivation layer, and the presence of contaminants or material defects. Several projects addressing such issues are currently being pursued within the

PowerAmerica Institute [16], such as North Carolina State University's investigation on package integration and novel edge termination, Cree's development of power modules, and National Renewable Energy Laboratory's (NREL) study of interface materials and thermal management solutions.

Supporting Electronics:

Supporting electronics constitute an essential part for the utilization of integrated SiC-based power systems. While some of these devices deemed compatible and suitable for use in SiC circuitry are presently available, others need to be, and are being, developed. In the power transistor area, for instance, although SiC parts are all n-type, the role of the complementary p-type device needed in many applications is presently achieved via a cascade design; more recently, however, USiC is offering a truly "normally-off" JFET to pair with its normally-on JFET, as reported earlier in Table III. Other ongoing efforts include the development of medium voltage gate drivers to enable fast switching of power transistors being pursued by Ohio State University and North Carolina State University within the PowerAmerica Institute [16].

Design tools:

Design of SiC circuits and the construction of efficient SiC-based power systems requires the use of accurate, validated circuit and/or device modeling tools. Such models and tools are a necessity for reducing design and production cycles. Several players are presently involved in the development and the use of calibrated compact models for inclusion in industry standard simulation tools for enabling modeling and simulation of SiC devices and circuits. For instance, CoolCAD Electronics is working on the development and commercialization of SPICE circuit models and CAD tools for SiC MOSFET [42] and SiC JFET [16] devices. Other organizations are using these tools and other models for devices' dynamic electrothermal simulation [43]. A review of compact and numerical models that have been developed for SiC power devices can be found in [44]-[45].

Reliability:

Besides cost, reliability of SiC devices has been a major factor in slowing penetration of this technology into the power electronics sector. Tremendous progress, however, has been achieved in the last few years by the semiconductor industry by producing cost-effective parts and improving reliability through the use of innovative fabrication processes resulting in good quality, large-size wafers. As a result, failure-in-time (FIT) rates have been reduced dramatically to a level comparable to, and in some instances, lower than those for Si parts. For example, a field failure rate with 0.12 FIT was reported for Cree's SiC MOSFETs and Schottky diodes, covering a span of 970 billion device-hours between 2004 and 2014 [46]. Similar research work predicted a FIT rate <10 with 90% confidence interval upon stress testing of GE 1.2 kV, 30A SiC MOSFETs under a gate bias of 20 V and a junction temperature of 150 °C [47].

While some reliability issues pertain to the semiconductor material itself, others are induced by the operational environment. Those intrinsic to the material arise from crystal defects that include micropipes, basal plane dislocations, and threading edge dislocations, amongst others. Micropipes are super screw dislocations (effectively holes) which might penetrate the entire crystal, and are usually formed during nucleation processes and growth surface morphology; they affect the high electric field capability of SiC devices. Micropipes, which normally lead to reduced yield, are no longer considered a major problem since their densities have been greatly reduced by manufacturers [48], with some even offering micropipe-free substrates [35], [49]. Basal plane dislocations have been described as "islands of single-crystal SiC with a displaced basal plane" [50], where the basal plane is the plane perpendicular to the principal axis of the crystal. In the presence of electron-hole recombination, these basal plan defects transform into triangular-shaped stacking faults, which tend to degrade forward voltage characteristics of SiC p-n diodes and MOSFET body diodes, and degrade current gain in SiC BJTs [48], [51]. Threading edge dislocations are usually one dimensional defects on the wafer surface occurring by the removal or insertion of an extra half plane of atoms between two lattice atomic planes, resulting in higher leakage current and lower breakdown voltage of SiC diodes [51]. It was reported that 90% of basal plane dislocations present in the substrate convert into threading edge dislocations during the homoepitaxial growth process with the conversion rate depending on the off-orientation angle, epitaxy growth parameters, and substrate preparation [48]. Proper processing of surface passivation seemed to alleviate this problem, and other proprietary techniques were reported to prevent propagation of stacking faults [52].

Another reliability issue pertaining to SiC devices is the quality of the SiC/SiO_2 interface in a MOSFET structure. Threshold voltage instability has been shown to occur under high gate field and temperature due to the large number of electrically active SiO_2 and SiO_2 interface states [53] - [54]. These states are formed upon the injection of electrons or holes from the SiC into the oxide when a positive or negative potential is applied to the gate, respectively. While typical instabilities of the threshold voltage amount to about 0.25 V at room temperature, much larger instabilities are observed following high temperature gate-bias stressing [54]. Newer-generation commercial devices exhibit reduced threshold voltage instability, and unique circuit designs that limit the levels of gate bias can also render the threshold voltage shift insignificant [52]. In addition to the gate bias, the electric field stress level in the oxide is determined by the oxide material and its thickness. Due to the mismatch in the dielectric constants of the SiC and SiO_2, enhancement of the electric field takes place in the oxide, reaching about 3 times higher than that in SiC [48]. Intensification of the field in the oxide layer contributes to the creation of tunneling currents, the emission of carriers from the semiconductor or from metal regions to the dielectric, resulting in time-dependent dielectric breakdown [55]. Recent development of high-quality oxide, coupled with appropriate oxide processes and new device structure, has greatly improved the reliability of emerging SiC devices [56]. Such progress has resulted from the use of high dielectric constant material leading to improvement in channel mobility [57]-[59], or nitration of the stacked gate dielectric causing reduction in interface trap densities [60]-[63].

Operating conditions such as environments where extreme temperatures and/or radiation are present also affect the reliability of SiC power devices. As mentioned earlier, the application of gate-bias stressing can cause instability in the threshold voltage of SiC MOSFETs. It is speculated that the drift in the threshold voltage, which has been observed for devices from three different manufacturers, even at room temperature, arises from the presence of near-interfacial oxide traps [64]. Under the influence of a high gate oxide field and high temperature, instabilities in the threshold voltage of both SiC MOSFETs and MOS capacitors get exacerbated due to the activation of additional gate oxide traps related to an oxygen vacancy defect known as an E' center [65] and electrically active states in the bulk SiO_2 and in the SiC/SiO_2 interface regions [66]. As indicated previously, progress is being made to limit these instabilities by decreasing the precursor oxide defect sites through improved processing methods and fabrication techniques.

Another environmental aspect affecting reliability of SiC power devices is exposure to radiation encountered in terrestrial as well as space applications. The terrestrial neutron environment and high-altitude cosmic rays form a hazard to SiC power electronics reliability, and are actually driving some of the interest in radiation-hardening of SiC parts. SiC diodes and MOSFETs, for example, are reported to exhibit SEB under exposure to terrestrial neutrons [67]-[69]. A neutron does not ionize charge but instead can collide with a SiC lattice atom, generating a charged primary knock-on (recoil) atom which can then deposit its energy through charge ionization along its path of travel before coming to rest. It is believed that this highly localized charge in the presence of the high electric field strength typical of SiC power devices can induce SEB through rapid heat generation that exceeds the temperature for SiC sublimation before it can be dissipated [68]. Importantly, as suggested in [69], the parasitic bipolar junction transistor in a power MOSFET does not play a role in SEB. This finding has important ramifications for hardening SiC MOSFETs against SEB: methods commonly used in silicon MOSFETs to reduce SEB susceptibility may not be applicable to SiC MOSFETs. In the space arena, electronics are bombarded by charged particles during spacecraft trajectory through Earth's Van Allen belts and in interplanetary space. The impact of radiation may be very costly as it can lead to system malfunction, or perhaps result in failure of an entire mission [70]. Radiation-induced damage to electronic parts may result in performance degradation, transient effects, or catastrophic failure. In general, semiconductor devices are prone to radiation effects through the generation and trapping of charges in oxides (total ionizing dose (TID) effects), introduction of current or voltage transients by individual ion strikes that can result in a change in the state or performance of the device (single-event effects (SEE)), and lattice structure disruption (displacement damage). TID radiation effects tend to build over time, leading to device performance degradation and possibly eventual failure. SEE are caused by the passage of a single charged particle through a sensitive region in the device's structure and can be non-destructive or destructive in nature. A literature search on the effects of radiation on SiC devices revealed the following:

- Several academic institutions, private companies, and government and space agencies are heavily involved in investigating radiation effects on such devices.
- Many researchers/groups have found good tolerance of SiC devices to TID radiation [71]-[77]; and some SiC JFETs and Schottky diodes are marketed with TID radiation tolerance >100 krad(Si) [78].
- All SiC power devices tested have shown a significant susceptibility to heavy-ion induced permanent degradation and neutron, proton, or heavy-ion induced destructive SEE when biased within their rated voltage in the off-state, i.e., in a voltage-blocking condition [79]-[84]. For example, SiC Schottky diodes were found to exhibit gradual increases in leakage current with increasing fluence under heavy-ion exposure at sufficiently high reverse-bias voltages [81]-[83], and similar work reported permanent damage to SiC Schottky barrier diode due to charge collection induced by heavy-ion irradiation at high bias voltages [82]-[83]. Heavy ion SEE tests on SiC power MOSFETs also revealed substantial degradation of leakage current that worsens with increasing temperature [84]. In [80] and [84], four modes of heavy ion responses were reported for SiC MOSFETs, as a function of the drain-source voltage when the gate was grounded: At very low bias, permanent latent damage to the gate oxide as a function of fluence; at higher bias, both gate and drain leakage current measurable during ion exposure; at still higher bias, drain-leakage dominated permanent degradation; and finally, SEB with collateral gate oxide rupture or combined SEB/SEGR event. These findings are in keeping with those of [81] for Schottky diodes, but with the addition of gate leakage modes.

With the continued growth in space programs and aerospace satellite business, on-board electronics need to be radiation-hardened to assure mission success; if SiC parts are to be used, the issue of susceptibility to heavy ions needs to be resolved. In addition, as reported in [82], the heavy-ion induced degradation likely affects the onset of catastrophic failure such that appropriate SEE test methods may need to be developed to yield meaningful test data that allow prediction of on-orbit performance and risk calculations, as well as accurate comparison of performance across device offerings.

Some techniques for reliability risk mitigation could be implemented with some pertaining to device fabrication and geometry, as mentioned earlier in the availability of newer-generation SiC parts with fewer defects and more stable oxides, while others focus on the configuration, design, or energizing pattern of the power system. Some of these latter mitigation methods involve, however, penalties in both device area and power that significantly erode the performance and integration density improvements afforded through the use of the SiC technology [85].

Conclusion

SiC, a wide bandgap semiconductor with thermal conductivity over three times of that of silicon, has the ability to operate at high voltages and at extreme temperatures, is well suited for high frequency operation, and has the potential for making a huge impact on the development of next-generation high-power electronic systems. This report documents some issues pertaining to SiC technology and its application in the area of power electronics. It also serves as a body of knowledge in reference to the development and status of this technology obtained via literature and industry survey as well as providing a listing of the major manufacturers and their capabilities. Finally, limitations affecting the full utilization of this technology are identified, and reliability issues pertaining to commercial SiC-based electronic parts, are addressed.

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